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Diagenetic Control on Porosity Development in Early Eocene Carbonate Reservoirs of Potwar Sub-Basin, Pakistan

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ABSTRACT

The Eocene carbonates of Sakesar and Chorgali rock units are the main oil and gas producing horizons in Potwar sub-basin of Pakistan. Petrographic analysis of core samples of wells from six different fields, demonstrates that diagenesis has played the major role in the development of porosities in the reservoirs of these two formations. Dolomitization and solution are the major diagenetic processes involved in the development of intercrystalline, moldic and vuggy porosities; whereas, structural deformation has resulted in joint and fracture porosities. Effective porosities, within the carbonates of the two rock units, are almost confined to the northwestern portion of the Potwar region; whereas, in the south-eastern part, open pore spaces are almost not existing.

INTRODUCTION

Potwar sub-basin is a part of Upper Indus Basin (Figure 1), which is bounded by Salt Range in the south and Main Boundary Thrust (MBT) in the north, whereas the eastern limit is marked by the River Jhelum and the western boundary by the River Indus (Figure 2). The Potwar sub-basin is one of the first areas explored for petroleum in the world (Khan et al., 1986). The first commercial oil well was drilled in 1914 by Attock Oil Company, which also proved to be the first oil producing well in the South Asian Sub-continent. Since then more than 40 structures have been tested through drilling, and more than a dozen structures have produced oil on commercial scale in the Potwar sub-basin.

In the Potwar region oil has discovered at different stratigraphical levels, such as, in Paleocene-Eocene carbonates, Jurassic sandstones, Permian sandstones and limestones and Cambrian sandstones. Among these reservoir intervals; however, Early Eocene carbonates of Sakesar and Chorgali formations, have been historically the main oil and gas producing horizons.

This study is based on the previous works and current updates on depositional environment and diagenetic changes, inferred through the petrographic analysis of core samples of carbonates of Sakesar and Chorgali formations, collected from the wells, i.e., Adhi7 (PPL), Balkassar-8 (PPL), Chak Naurang-1 (PPL), Dhulian-37 (POL), Meyal-2 (POL) and Dakhni-3 (OGDC). Previously Dakhni-3 and Meyal-2 wells were studied by Jurgan et al. (1988), Adhi-7 by Mujtaba et al. (1990), Chak Naurang-1 by Mujtaba and Abbas (1991), Balkassar-8 by Mujtaba (1992) and Dhulian-37 by Mujtaba (1993).

LITHOLOGICAL CHARACTERISTICS

Carbonates of Chorgali Formation is characterized by tidal flat environments (specially intertidal to supratidal) and constitute of mostly pervasively dolomitized micrite with varying components of intraclasts, i.e., dolomitized micrite to intraclast-bearing micrite to intramicrite in terms of Folk's classification and dolomitized mudstone to dolomitized intraclastic wackestone to packestone in terms of Dunham's classification. Intraclasts are of different shapes and sizes and look to be disintegrated and reworked products of stromatolites. This rock unit is also characterized by thinly bedded to laminated carbonates with common occurrence of anhydrite layers and nodules in the northwestern portion of the Potwar region. Bioclastic components are rare and seams to be transported, probably through tidal and storm currents. The early diagenetic nature of dolomite (fabric retentive type of dolomitization) and common occurrence of anhydrite layers and nodules and presence of solution collapse breccea, indicate sabkha type of paleosettings along the north-western portion of the study area.

Carbonates of Sakesar rock unit are characterized by shallow marine environment with restricted circulation, and consist mostly of micrite with varying frequency of bioclasts, i.e., micrite to fossiliferous micrite to biomicrite in terms of Folk's classification and mudstone to bioclastic wackestone to packstone in terms of Dunham's classification. In some of areas, specially in the north-western portion, the upper part of the sequence is dolomitized with varying degree. The rock unit, in the exposed sections, is massive to medium bedded and typically nodular. Bioclastic components consist mostly of benthonic forams, echinid fragments, ostracods, gastropods and pelecypods. Benthonic forams are mostly represented by Rotaliidae, Nummulites, Assilina, Alveolinidae, Soritidae, Textulariidae, Lockhartia, Operculina and Discocyclina.

DIAGENETIC ALTERATIONS

Diagenetic evolution of limestones consists of a continuos sequence of processes that modify their depositional texture and composition through time from deposition to deep burial. The fundamental feature of the diagenesis of limestones is their interaction with marine and meteoric waters and with subsurface solutions. Each of these fluids leaves a unique diagenetic imprint at the time of its reaction with limestone. This imprint can be considered as a distinct diagenetic phase, although this imprint may be largely or totally destroyed by subsequent diagenetic phases.

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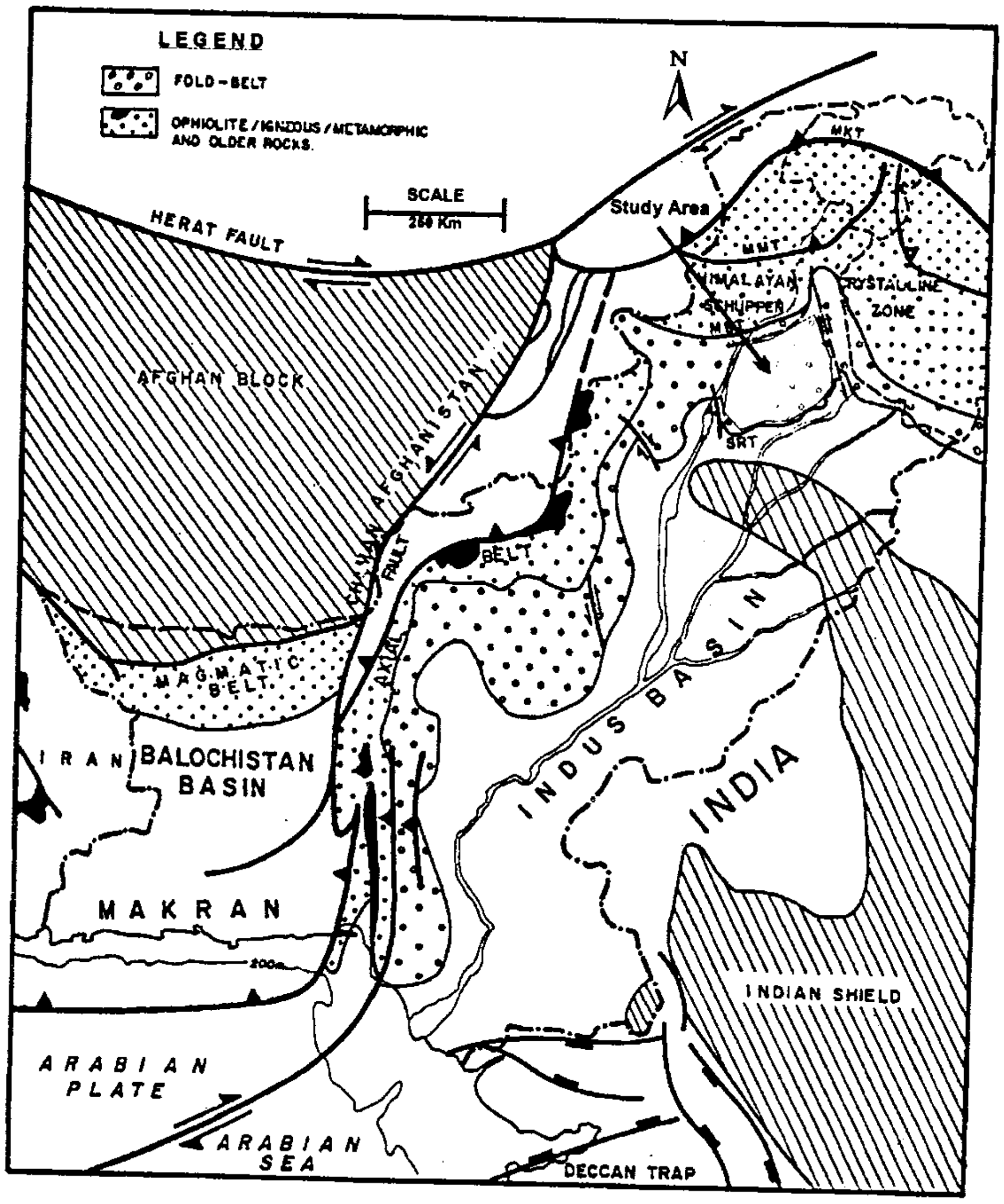

Figure 1- Generalized tectonic map of Pakistan, showing the location of study area (After Kemal, 1992).

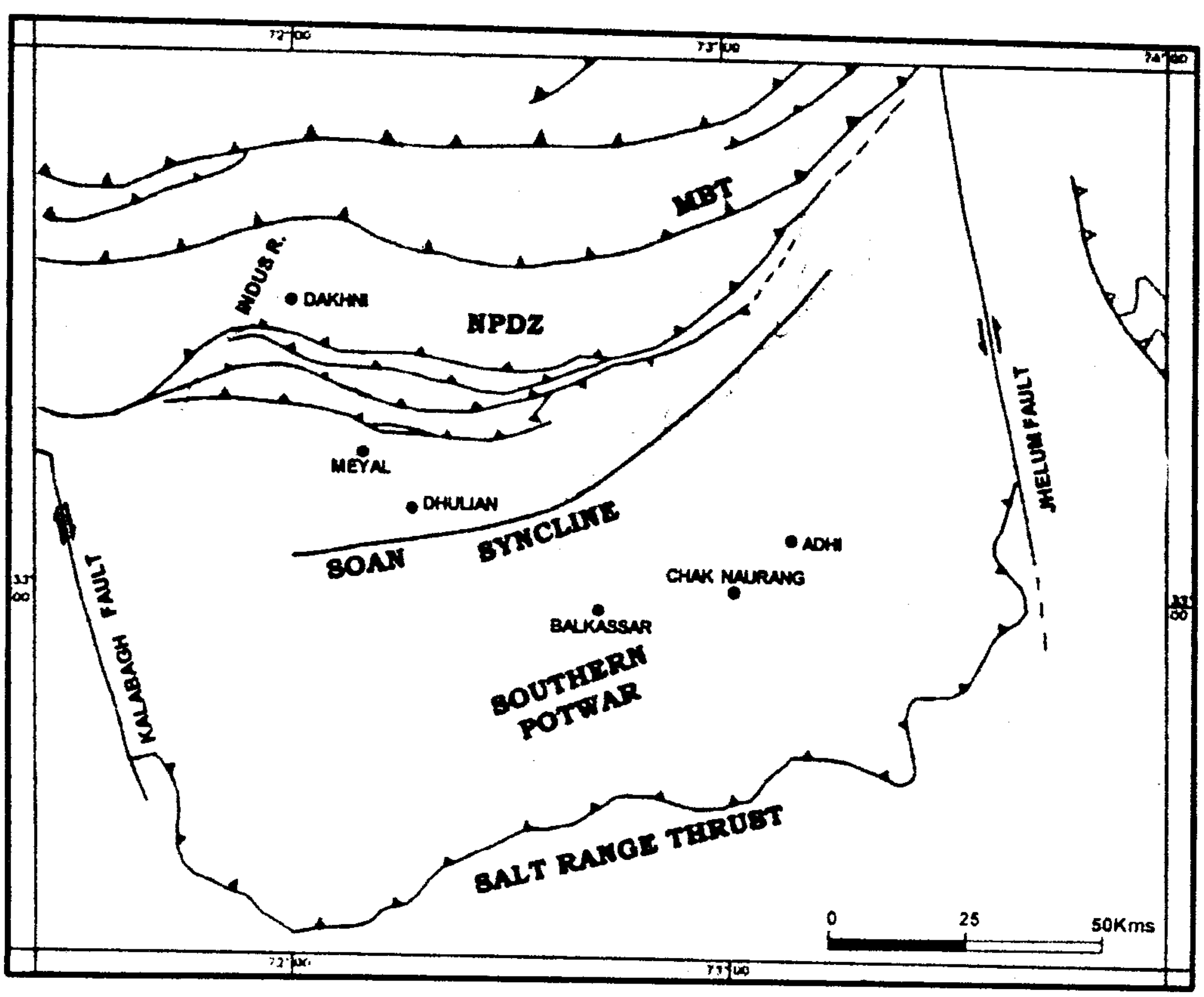

Figure 2- Potwar sub-basin, showing the location of studied wells.

Shallow marine carbonate sediments consist of metastable carbonate phases, such as, aragonite and high-Mg calcite (Milliman, 1971; Bathurst, 1974), which are easily dissolved and recrystallized by fresh waters or mixtures of meteoric and marine waters, which are encountered in surface and shallow subsurface conditions (Longman; 1980, James and Choquette, 1984). One of the major impacts of meteoric water diagenesis is the basic rearrangement of calcium carbonate by dissolution of grains and the reprecipitation of calcium carbonate as cement in pore spaces.

Carbonates, not extensively altered during early diagenesis, are particularly susceptible to chemical compaction processes, such as, grain-to-grain pressure solution and stylolization during burial because of the relatively high solubility of calcium carbonate (Bathurst, 1975). Aggressive pore fluids are common in the deep subsurface because of high temperatures, dissolved organic acids, carbon dioxide, hydrogen disulfide and other components released into pore fluids during mineral phase changes and thermal degradation of organic matter and hydrocarbons (Sassen & Moore, 1988). Following diagenetic processes have greatly modified the original carbonate sediments of the Sakesar and Chorgali formations.

- Bioturbation has almost completely reworked the original sediments of specially Sakesar limestone.
- Neomorphism caused the inversion of aragonitic composition of bioclasts to low Mg calsite. This mechanism has also resulted in the recrystallization of lime mud to relatively coarser calcitic mosaic, giving rise the patches of microspar.
- Shallow burial mechanical compaction has resulted rearrangement and closer packing of grains, as well as, plastic deformation of bioclasts, such as, Alveolinidae tests.
- Early diagenetic dolomitization has resulted fabric retentive, fine to very finely crystalline dolomite of Chorgali Formation. This dolomitization is restricted to intertidal to supratidal environments.
- Seepage reflux of dolomitizing fluids have probably resulted the dolomitization of the upper portion of Sakesar limestone. These dolomites are fabric destructive, medium crystalline and sometimes with interlocking texture. This second phase of dolomitization is generally fabric selective, i.e., lime mud is dolomitized and skeletal grains remains unaffected.
- During the second phase of dolomitization, partial or complete leaching of aragonitic bioclasts of coral, green algae, pelecypods and gastropods resulted in the development of open voids (molds). The fluid also resulted in the dissolution of high Mg calcite grains, such as, milliolids and Alveolinids etc.
- Subsequently the open voids (molds) were mostly filled with coarsely crystalline cements of calcite and evaporites (gypsum/anhydrite). The phenomenon of occlusion of open molds is more common in the central and eastern portion of the study area. In the western portion, however, some of the molds and vugs escaped subsequent occlusion.
- Chemical compaction, during deep burial, played the most significant modifying factor, specially for the carbonates of eastern and southern portion of the region. Chemical compaction (pressure dissolution) has resulted in the development of nodular structure, grain-contact sutures (Figure 16), stylolites and microstylolites (Figure 19) and sometimes sutured seams (Figure 18).
- Third phase of dolomitization is related to deep burial pressure dissolution, where dolomite crystals are confined to the microstylolites and sutured seams. Such dolomites are fine to medium crystalline and mostly subhedral in shape.
- Fracturing is very common, specially, in the north-western portion of the region. The fractures have developed due to deformation related to the intense tectonic activity in the north-western part of the Potwar sub-basin.
- Leaching of cements which have filled the previously developed open molds, vugs and fractures. This late diagenetic solutioning of cements has been attributed to the above mentioned aggressive pore fluids in the deep subsurface because of high temperatures, dissolved organic acids, carbon dioxide and thermal degradation of organic matter and hydrocarbon etc.

POROSITY DEVELOPMENT

Pore systems in carbonates are much more complex than in siliciclastics. This complexity is a result of the overwhelming biological origin of carbonate sediments that results in porosity within grains, growth frame work porosity within reefs, and the common development of secondary porosity due to pervasive diagenetic processes such as solution and dolomitization, affecting the more chemically reactive carbonates throughout their burial history.

Choquette and Pray (1970) developed a workable carbonate porosity classification, which is still widely used. Carbonates of Early Eocene age of Potwar sub-basin display secondary porosities, which developed at any time after final deposition. Secondary porosity may be either fabric selective or not, depending primarily on diagenetic history. For example, moldic porosity is commonly fabric-selective because of the preferential removal of certain fabric elements from the rock, such as aragonitic ooids and bioclasts early during mineral stabilization, or anhydrite, gypsum or even calcite from a dolomite matrix later in the diagenetic history of a sequence. On the other hand, phreatic cavern development commonly cuts across most fabric elements, is not fabric-selective, and is controlled primarily by joint systems. A brief description of development of secondary porosity, noticed in the core samples of the selected wells is as follows:

Dakhni Oil Field

Out of the six selected wells, core samples of Dakhni oil field display the best development of various types of open porosities. The most prominent diagenetic processes which resulted in the development of secondary porosity in carbonates of Sakesar and Chorgali rock units, in Dakhni oil field, are: the late diagenetic dolomitization (mainly due to seepage reflux dolomitizing solution), near surface and deep burial dissolution, deep burial chemical compaction (pressure dissolution) and fracturing related to tectonic activities during uplift of region.

Late diagenetic dolomitization has resulted in the development of intercrystalline porosity (Figure 3) and intraparticle porosity (Figure 4) due to leaching of undolomitized calcite remains of bioclasts. Near surface dissolution of evaporites has developed porosity within the calliopes breccia (Figure 5). Deep burial dissolution, caused by corrosive fluids resulted in the development of moldic (Figure 6) and vuggy (Figure 7) porosities. Deep burial chemical compaction has developed stylolitic porosity (Figure 8). Tectonic activities during uplift of the region resulted fracture porosity (Figure 9), specially within the dolomitic facies of the two rock units i.e. Sakesar and Chorgali formations.

Meyal Oil Field

Core samples of carbonates of Sakesar and Chorgali formations, at Meyal oil field, display three main types of secondary porosities, i.e. moldic, vuggy (Figure 10) and fracture (Figure 11). Moldic and vuggy porosities were developed during late diagenesis due to aggressive pore fluids in deep subsurface. Fracture porosity was developed due to tectonic activities during uplift of region. It may be mentioned over here that joints and fractures are frequently healed (filled with) in limestones due to calcite cementation, whereas, in dolomites such openings are mostly remained open. Anhydrite nodules and layers are very common at this location interbedded with carbonates, as they remained out

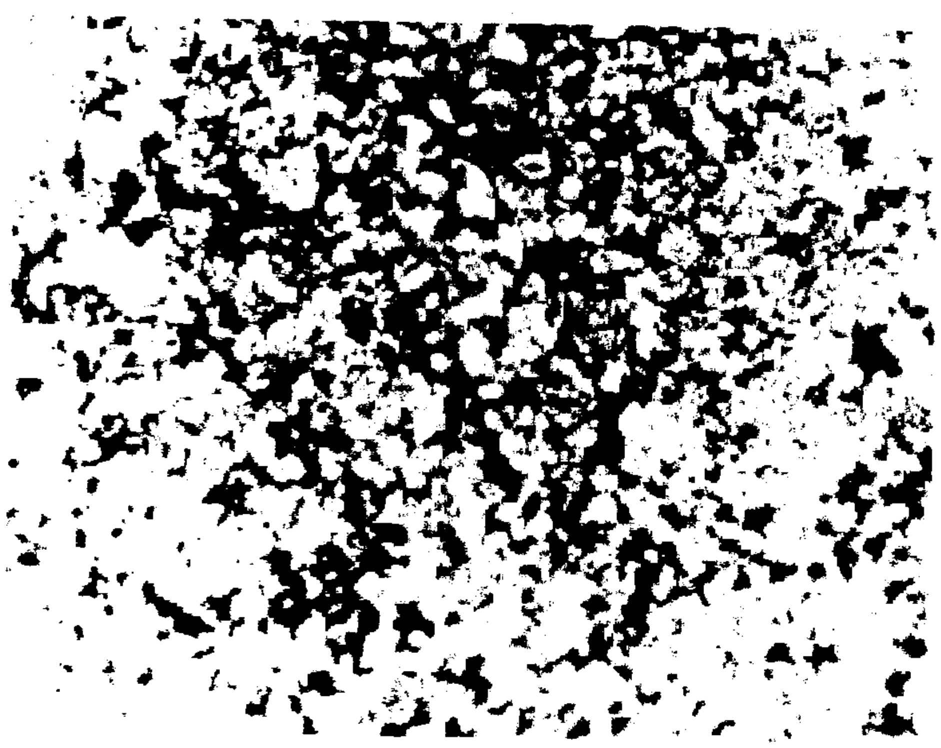

Figure 3- Intercrystalline porosity (Dakhni field, Mag. X40).

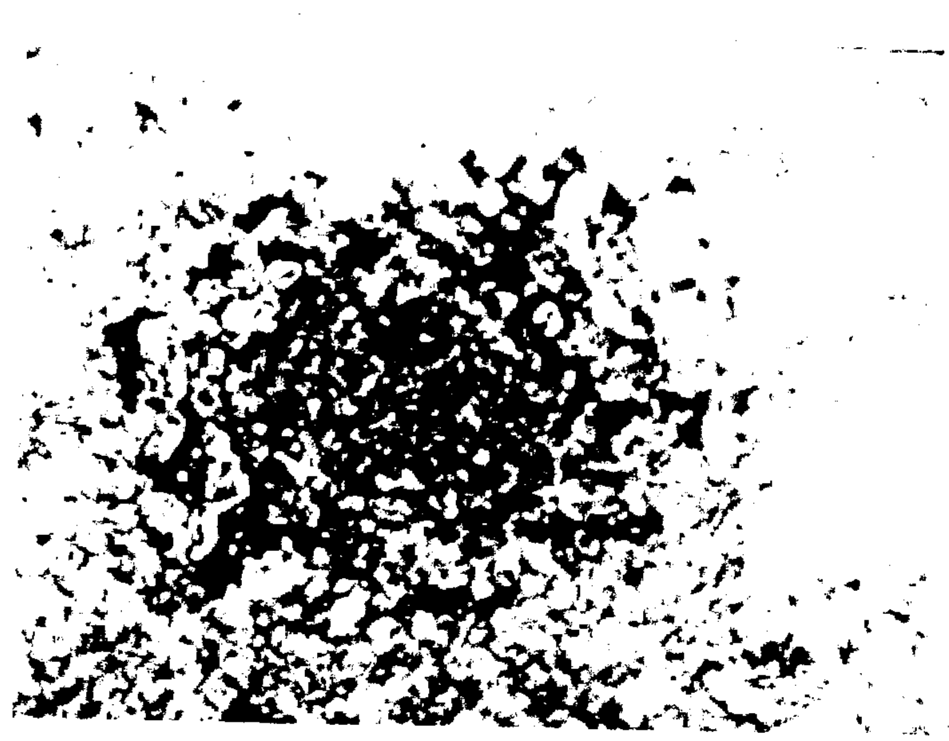

Figure 4- Intraparticle porosity (Dakhni field, Mag. X90).

Figure 5- Solution collapse breccia (Dakhni field, Mag. X40).

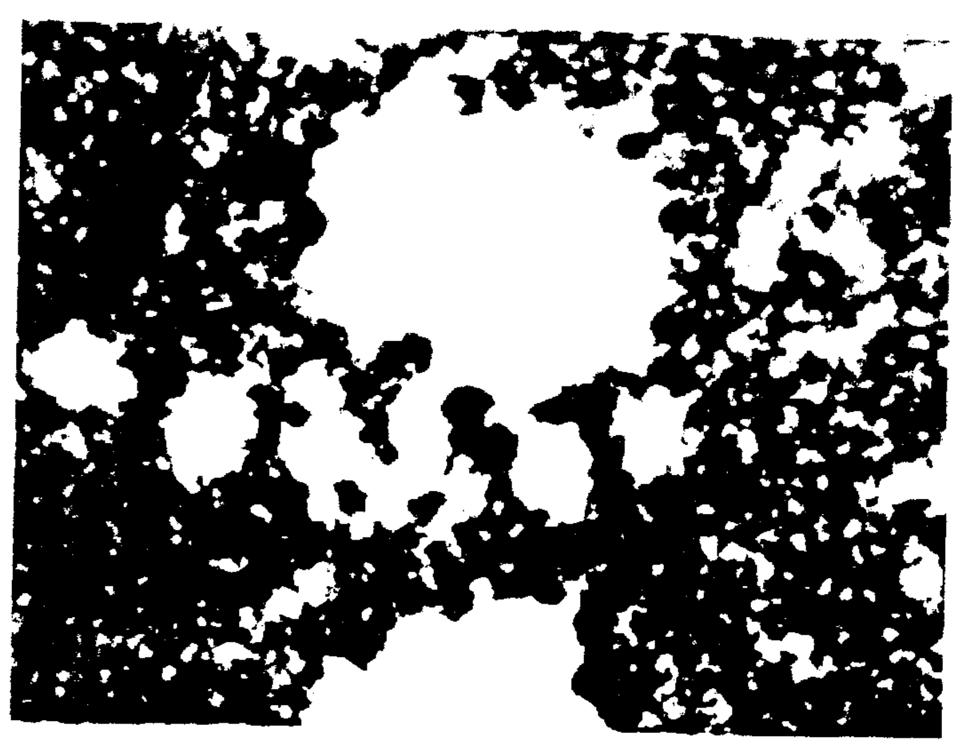

Figure 6- Moldic porosity (Dakhni field, Mag. X40).

of the influence of undersaturated surface water. This is the reason that porosity development, on account of the solution collapse breccia, is not common at this location, contrary to the Dakhni oil field where evaporites are not present and phenomenon of solution collapse breccia is widespread.

Dhulian Oil Field

At Dhulian oil field, core samples display mainly only one type of open pore spaces i.e. moldic porosity (Figure 12) within the carbonates of Sakesar and Chorgali formations. These moldic porosities were developed due to leaching of bioclasts (mainly forams) as the result of corrosive nature of fluids in deep subsurface. These fluids were probably generated in connection with the release of CO_2 during the thermal degradation of organic matter and hydrocarbons.

Chak Naurang Oil Field

As compare to the Dakhni, Meyal and Dhulian oil fields, carbonate sequence of Early Eocene at Chak Naurang oil field is rather tight. Core samples reveals some localized moldic, stylolitic and fracture porosities. Moldic porosity (Figure 13) was developed probably due to the leaching of bioclasts (mainly forams) through aggressive fluids in deep subsurface environment. Stylolitic porosity (Figure 14) was developed due to the chemical compaction of the carbonate sequence during late diagenesis. Fracture porosity (Figure 15) is the result of tectonic deformation of the strata during uplift of region.

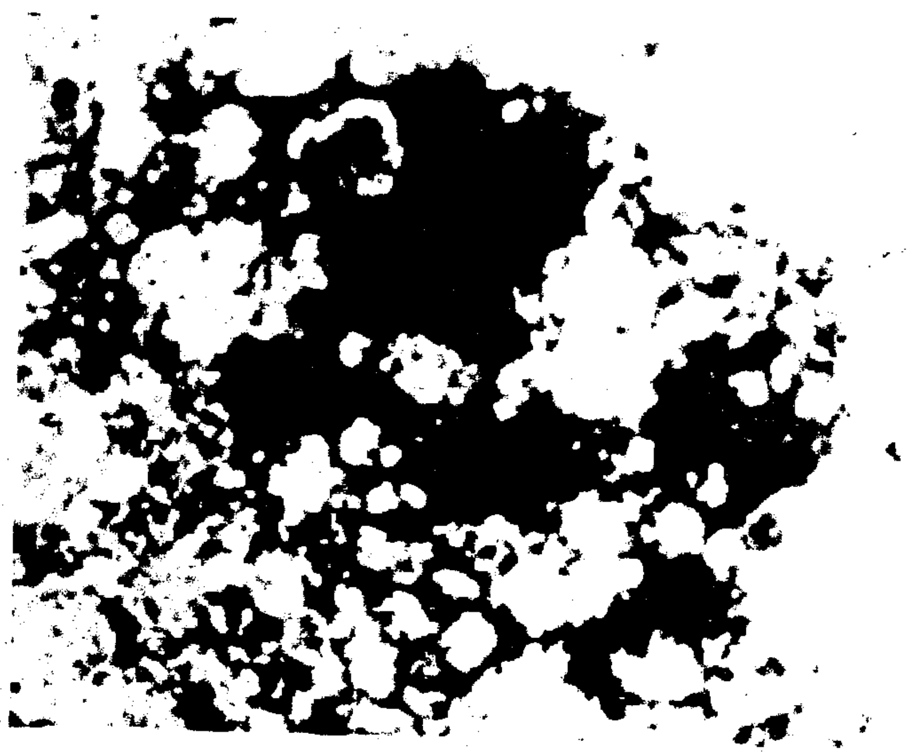

Figure 7- Vuggy porosity (Dakhni field, Mag. X90).

Figure 8- Stylolitic porosity (Dakhni field, Mag. X90).

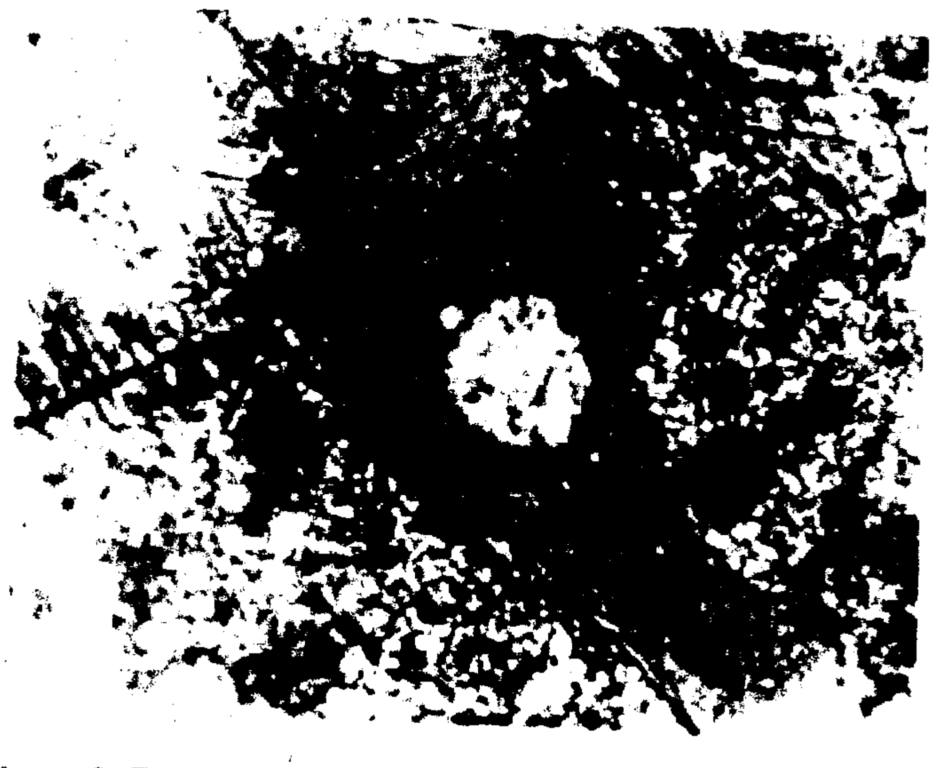

Figure 9- Fracture porosity (Dakhni field, Mag. X90).

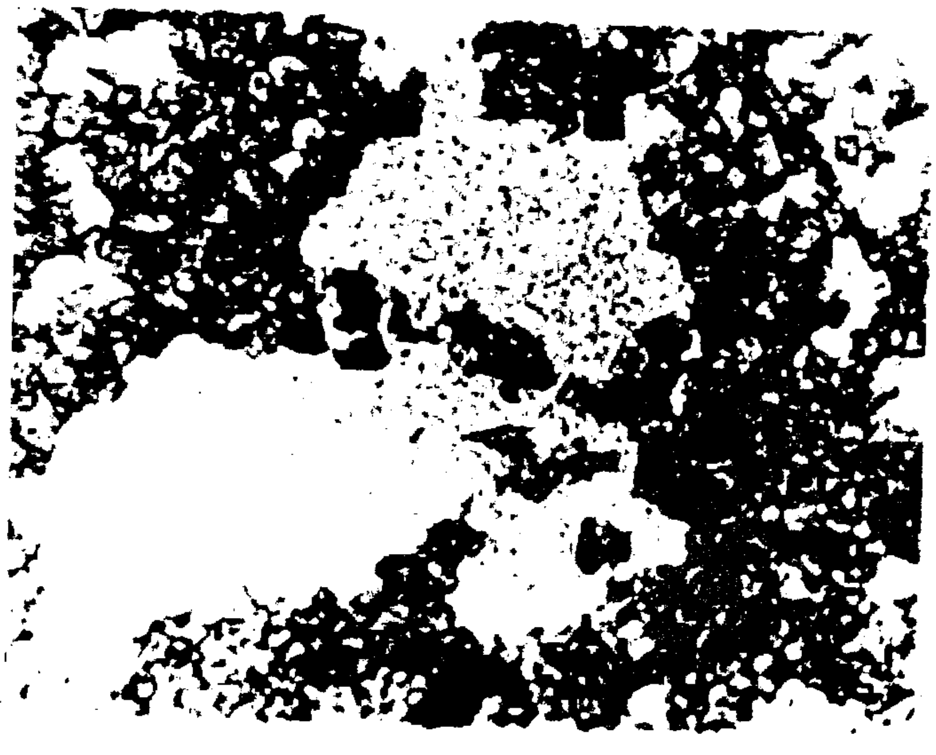

Figure 10- Vuggy porosity (Meyal field, Mag. X90).

Adhi Oil Field

Core samples of Sakesar and Chorgali carbonates, at Adhi oil field, indicate that the diagenesis, specially pressure dissolution (chemical compaction), has rather destroyed the porosity. The intensity of the process can be seen by the development of grain-contact sutures of Assilinal bioclasts (Figure 16). Only very localized development of vuggy porosity (Figure 17) was noticed. However, microstylolitic seam (Figure 18) are very common throughout the carbonate sequence. It is presumed that joints, fractures and stylolites have played the major role in the development of the present low porosity within the carbonate sequence of Sakesar and Chorgali formations at this location.

Balkassar Oil Field

Core samples of carbonates of Early Eocene age at Balkassar oil field, reveals that diagenesis has almost completely destroyed any existing porosity, except the development of microstylolites (Figure 19). There is no existence of Chorgali carbonates at this location, neither any dolomitization has taken place. Moreover, there is no sign of occurrence of evaporites within the Sakesar limestone, which could have resulted solution breccia related porosity, under the influence of surface water.

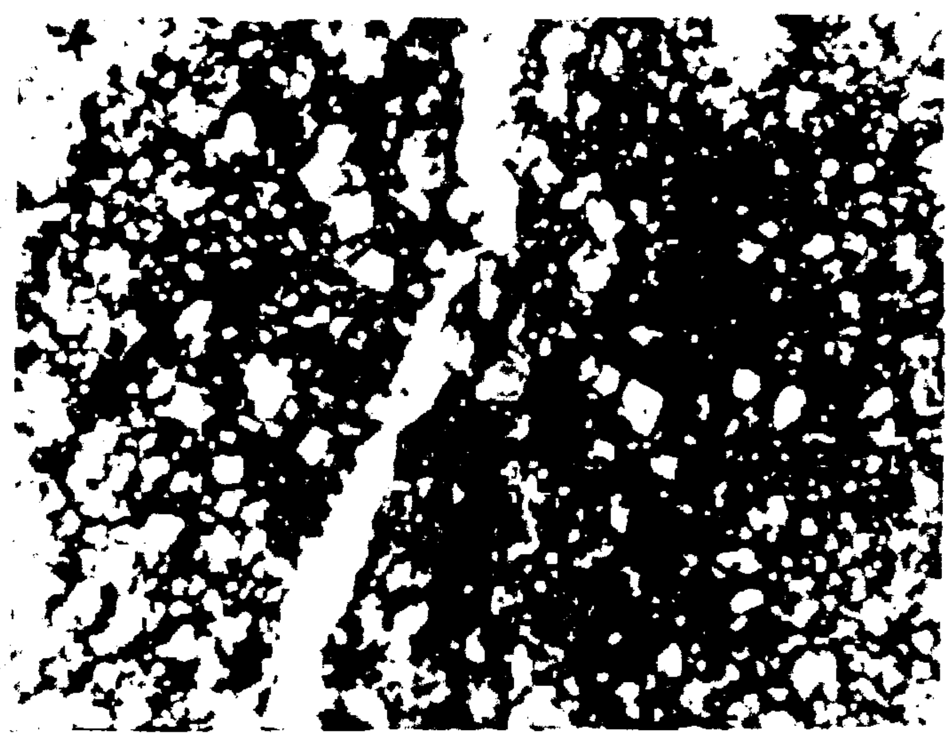

Figure 11- Fracture porosity (Meyal field, Mag. X90).

Figure 12- Moldic porosity (Dhulian field, Mag. X40).

Figure 13- Moldic porosity (Chak Naurang field, Mag. X40).

Figure 14- Stylolitic porosity (Chak Naurang field, Mag. X90).

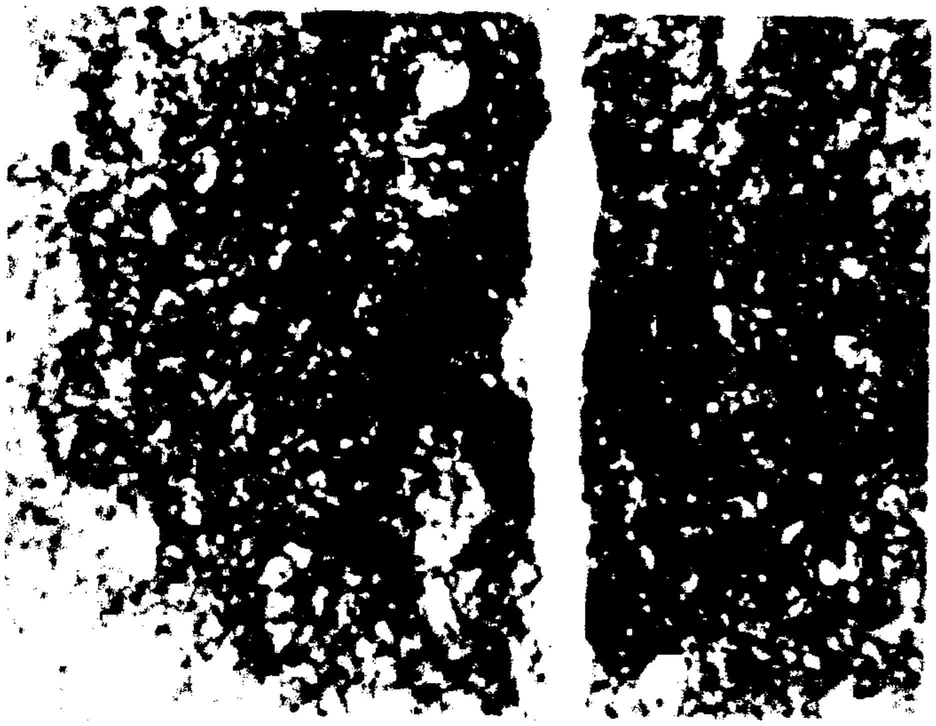

Figure 15- Fracture porosity (Chak Naurang field, Mag. X90).

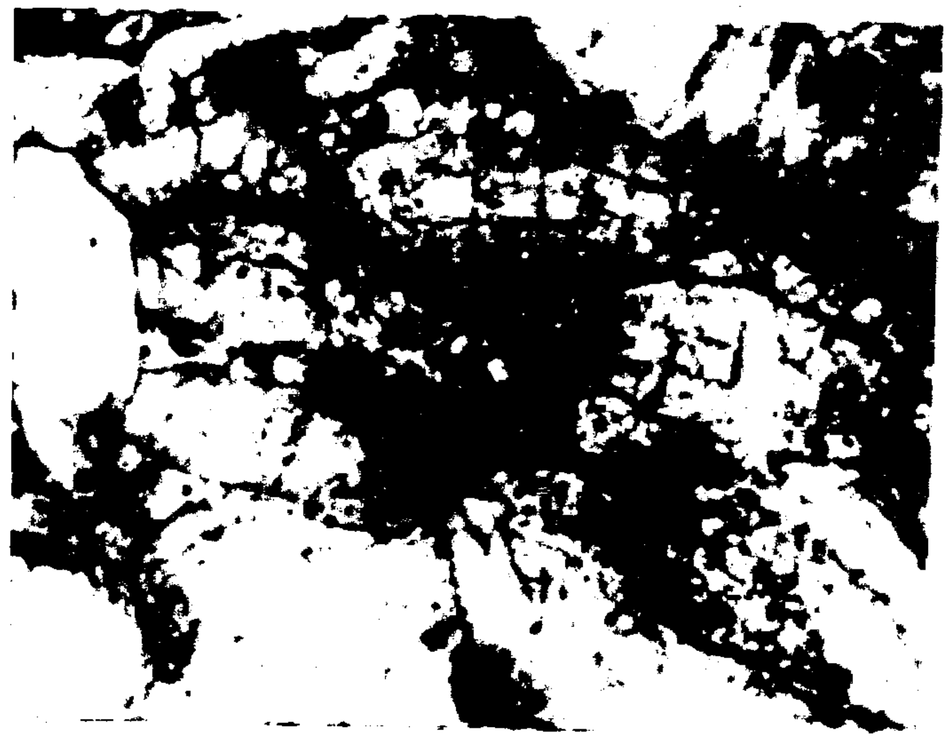

Figure 16- Grain contact sutures of Assilinal bioclasts (Adhi field, Mag. X40).

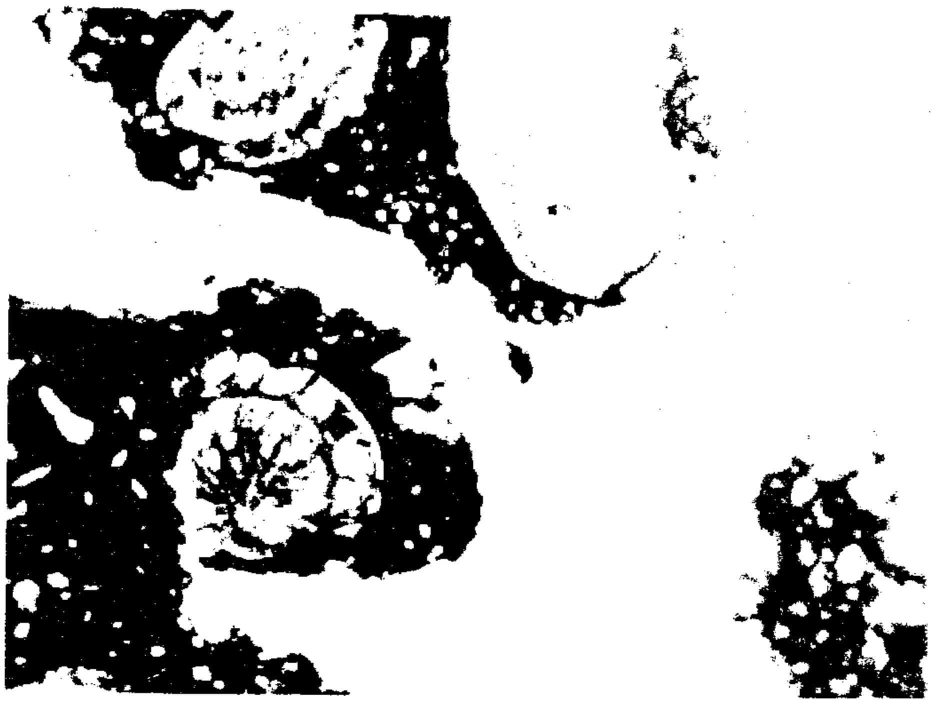

Figure 17- Vuggy porosity (Adhi field, Mag. X40).

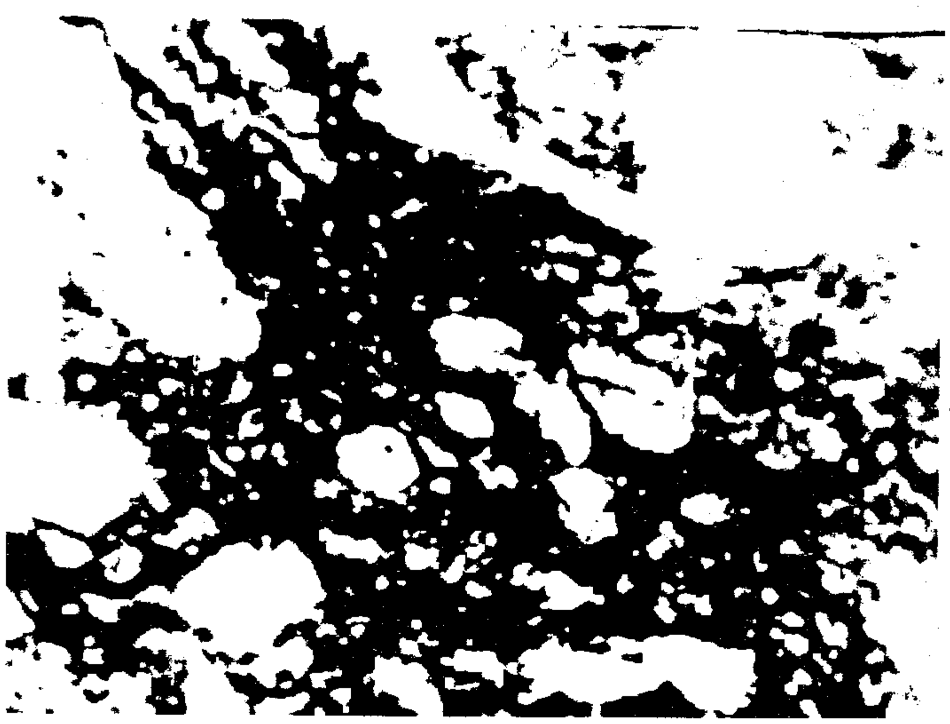

Figure 18- Microstylolitic seam (Adhi field, Mag. X90).

Figure 19- Microstylolitic seam (Balkassar field, Mag. X90).

POROSITY DISTRIBUTION

It has been described above that the open porosities are more developed in the core samples of the wells located in the north-western part than those within the core examples of wells located in the south-eastern portion of the Potwar region. This difference in the porosity development, in the north-western and south-eastern portions, is because of two factors, i.e. depositional and diagenetic. Depositional in the sense that during the time of deposition of the sediments of Chorgali carbonates, sabkha type supratidal environment was prevailing in the north-western portion; whereas, mostly subtidal environment was existing in the south-eastern portion of the study area. This interpretation is based on the non-existence of dolomitized upper portion of Sakesar limestone and also non-existence of evaporite minerals, which could have resulted in the development of widespread solution breccia under the influence of percolating fresh water during Middle Eocene to Oligocene time. This change in the environments in the two portions of the Potwar region resulted in the distinct diagenetic patterns, i.e., late diagenetic dolomitization (specially those related to the seepage-reflux mechanism) of upper portion of Sakesar limestone and development of solution collapse breccia due to dissolution of evaporites, which were existing in the north-western portion and lacking in the south-eastern portion of the region. Due to lack of these two diagenetic factors, intercrystalline, moldic and vuggy porosities could not be developed in the south-eastern portion. Moreover, joint and fracture porosities also not as effective in the south-eastern portion as those of within the north-western part, because open joints and fractures are mostly confined to the dolomitic sequence of the two rock units (Sakesar and Chorgali formations) in the north-west, whereas joints and fractures, which developed within the limestone facies in the south-east, have been filled by calcite cement.

CONCLUSIONS

- Diagenesis has played the vital role in the development of secondary porosities within the carbonate reservoirs of Sakesar and Chorgali formations in the Potwar sub-basin.
- Effective porosities include intercrystalline, moldic, vuggy and fracture types.
- Diagenetic processes, which have resulted in the development of secondary porosities within the Early Eocene carbonates, are mainly dolomitization, near surface and deep burial dissolution, chemical compaction and structural deformation. However, in the south-eastern portion of the Potwar region, chemical compaction has very adversely affected the porosity development.
- Effective porosity is widespread in the north-western portion of the study area, whereas, south-eastern portion displays almost negligible open pore spaces. It is, therefore, suggested that future exploration activities may be accelerated in the north-western portion, in case Early Eocene carbonates are considered as target horizons.

There are three main reasons for the very low porosity within the relevant carbonates in the south-eastern portion of the area: 1) non-development of sabkha type supratidal environment, 2) seepage reflux type of dolomitization and 3) non-existence of evaporates which could have resulted solution breccia under the influence of percolating fresh water.

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